

A REGENERATIVE FREQUENCY DIVIDER OF IMPROVED STABILITY

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ABSTRACT

This report describes the final development of three ten-to-one regenerative frequency dividers, dividing from 100 to 10 kc, 10 to 1.0 kc, and 1.0 to 0.1 kc. These dividers possess very stable operating characteristics for wide variations in plate voltage and input signal voltage, and, in addition, exhibit desirable self-starting and non-critical tuning characteristics as well as circuit simplicity and small physical size.

PROBLEM STATUS

This is the final report on the development of the three regenerative frequency dividers which was one phase of the problem. Work on the main problem is continuing.

AUTHORIZATION

Naval Research Laboratory Problem R10-23D.
NL 496-022

A REGENERATIVE FREQUENCY DIVIDER OF IMPROVED STABILITY

INTRODUCTION

In the maintenance and alignment of naval electronic equipment, highly stable harmonic and subharmonic frequencies derived from a secondary-standard crystal oscillator are frequently necessary. Therefore, Problem No. 36R10-23D (BuAer No. A-262-ED-R) was established to provide the major naval repair bases for aircraft electronic equipment with precision measuring and calibrating standards not only for audio and radio frequencies but for many other quantities such as amperage and voltage, both a-c and d-c. Work to be described in this report covers only a small phase of the over-all problem, namely, that of providing a number of frequencies below that of a secondary-standard crystal oscillator which will most desirably operate at 100 kc. These subfrequencies must possess the same degree of stability and frequency accuracy as the secondary-standard oscillator.

Specifically, the desired subfrequencies are 10 kc, 1.0 kc, and 0.1 kc. Thus, three frequency dividers are required, the first to divide from 100 to 10 kc, the second to divide from 10 to 1.0 kc, and the third to divide from 1.0 to 0.1 kc.

Two uses are foreseen for these dividers. The first is as a unit with the standard crystal-oscillator where input signal levels and operating conditions of the individual frequency-dividers will vary little if any. The second use is as individual frequency-dividers where input signal levels and operating conditions might vary radically, since inexperienced personnel are likely to operate the equipment without the caution and consideration of a laboratory scientist. Consequently, in drawing up the divider specifications, it was thought necessary to require the most fool-proof, reliable design possible—particularly with respect to variations of input signal voltage and changes in plate and filament supply voltage; self-starting; and spurious signal output. In other words, the frequency divider should operate normally with large variations in input signal voltage and with large variations in plate and filament voltages. Also the divider should be self-starting upon the application of signal and supply voltages and, to avoid misleading the user, must not have spurious outputs in the absence of one or more of the operating conditions.

With these requirements in mind, a search of the literature and available commercial designs was made in an attempt to find a suitable frequency divider for the problem. Models of the more promising circuits were constructed and evaluated. All of the ten-to-one frequency dividers were found to have a rather restricted operating range with respect to the level of input signal and the variation in plate and filament voltage, along with certain other limitations typical of given types. A number of the divider types would probably have given satisfactory service when permanently used as a unit with the secondary-standard crystal oscillator; since the divider input signals would then remain constant and the plate and filament supply voltages could be regulated. However, these frequency dividers are unsatisfactory for separate use where input signals are likely to vary appreciably

as are the supply voltages. For this reason more stable dividers are desirable. Also, as a matter of good design practice, it would be desirable to have less critical dividers for fixed operation, as well, to insure greater reliability and less sensitivity to tube changes, tube aging, temperature, etc. Since it was determined that no existing frequency divider design completely filled all problem requirements, it was decided to initiate development work on the most promising of the frequency dividers, the regenerative frequency divider,* in order to provide a unit suitable for the problem.

THEORY OF OPERATION

At this point it would be well to review the theory of regenerative frequency divider operation with the aid of the block diagram on Figure 1. The regenerative frequency divider consists of two vacuum tubes and two tuned circuits. The first tube, designated as the modulator, is a pentagrid converter type; and the second, designated as the harmonic generator, is a pentode. Each tube has a selective tuned circuit connected in its plate lead tuned to a frequency of f/n for the modulator and a frequency of $(n-1)f/n$ for the harmonic generator. Operation of the regenerative loop formed by these circuits may be described as follows. Intermodulation between the input frequency, f , and the harmonic generator output frequency, $(n-1)f/n$, produces in the modulator the sum and difference frequencies, $(2n-1)f/n$ and f/n . Since the modulator selective circuit is tuned to f/n , the modulator output frequency will be f/n . This modulator frequency is coupled to the divider output and to the harmonic generator, where it is multiplied by $(n-1)$ to produce the $(n-1)f/n$ frequency. Consequently, a condition exists where a continuous divider output frequency of f/n can be maintained, under favorable conditions, as long as an input signal, f , is present.

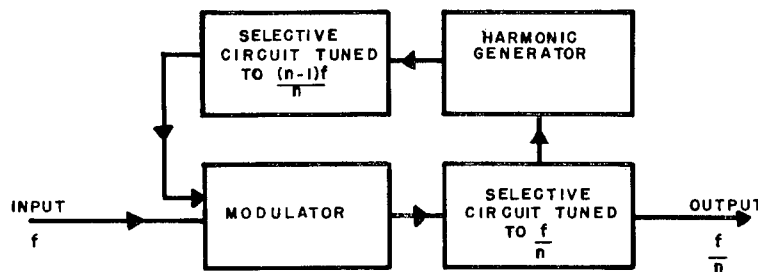


Figure 1 - Regenerative frequency divider block diagram

A schematic diagram of a regenerative frequency divider, representative of the latest advances in the art as published in the literature, is illustrated on Figure 2. A model of this divider was constructed, measured, and found to operate only over a five to ten percent range of input voltage and supply voltages. Resonant circuit tuning was also found to be critical, and the divider self-starting characteristic with application of input signal or supply voltages was somewhat unpredictable.

* Early development work on the regenerative frequency dividers is described in NRL Report 3580, "Improvements in Regenerative Frequency Dividers," by G. K. Jensen and F. E. Wyman, 9 Dec. 1949. It also contains an explanation for the choice of the regenerative frequency divider, as well as a rather complete mathematical analysis of this type of frequency divider.

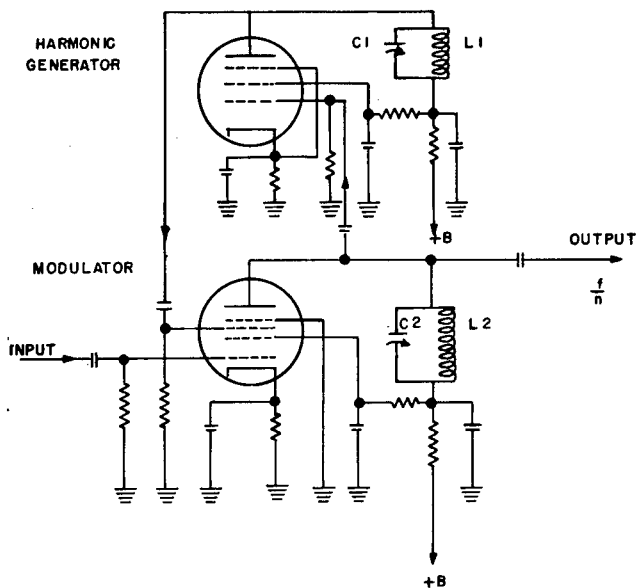


Figure 2 - Original regenerative frequency divider

The approach toward improved divider operating range and stability is indicated by the mathematical analysis presented in NRL Report 3580. It was shown that for stable divider operation the loop gain must be such that sufficient $(n - 1)f/n$ voltage is fed back to the modulator to sustain normal divider operation and, at the same time, an insufficient amount of f/n voltage fed back to cause self oscillation at the f/n frequency in the absence of the divider input frequency. Thus, the voltage ratio of $(n - 1)f/n$ to f/n frequencies at the harmonic generator output may be considered as an indication of divider stability—the larger the voltage ratio, the greater the stability. This stability will manifest itself as greater tolerance in loop gain and tuned circuit adjustments along with operation over greater ranges of input signal voltage and plate supply voltage. Greater $(n - 1)f/n/f/n$ voltage ratios may be obtained by higher-Q coils, improved tuned-circuit load isolation, more efficient harmonic production, and greater attenuation of the f/n frequency in the harmonic generator.

More stable divider operation over wide input signal amplitude variations may also be expected if the changes in grid biases and loop gain caused by these variations are minimized by some form of input signal clipping. Likewise, if the changes in tube currents and loop gain due to large shifts in plate voltage are minimized, improved divider performance can also be expected.

As has been emphasized, a regenerative frequency divider should have the ability to self-start normal division upon the application of a proper input signal. In prior art, this function has been dependent upon some supply voltage transient or an injected triggering signal. It would be much better if self-starting were accomplished in a positive fashion, to save extra trigger circuits, preferably by the input signal. This can be done by squaring the input signal by means of crystal diodes to cause ringing of the f/n tuned circuit, thus initiating normal loop operation.

Another important consideration is reproducibility; that is, it should be possible to construct additional dividers having identical characteristics to that of the original. In the past this has not always been possible.

CIRCUIT IMPROVEMENTS

Reference to the schematic diagram of the final 100- to 10-kc regenerative divider in Figure 3 will aid in describing the circuit improvements, also comparison of this figure with the original divider diagram in Figure 2 will further emphasize the circuit changes. The discussion will describe a divider of no specific frequency because the design principles herein achieved apply generally and component values may be scaled up or down to suit the particular frequency application.

One requirement for stable division is efficient harmonic production. In Figure 3, tube V_2 and the tuned circuit C_1L_1 comprise the harmonic producing and selecting elements, and tube V_2 was zero biased for nonlinear operation, causing distortion and harmonic production. In addition, even greater distortion was realized by making the input driving (coupling) impedance very large. A large coupling impedance is also advantageous from the standpoint of minimizing the loading on the modulator tuned circuit C_2L_2 in the plate lead of the modulator tube V_1 .

The selectivity of the two tuned circuits, C_1L_1 and C_2L_2 , as determined by the coil Q in the circuit, must be kept above a given minimum to provide selection of the desired signals and adequate suppression of undesired signals. The in-circuit coil Q is determined by the total load shunting the tuned circuits, and decreases with load. This load consists of the plate resistance of the associated tube and the circuit being driven, and should not exceed the value which reduces the Q below the acceptable minimum of 25 as determined experimentally.

Figure 4 shows the Q of two separate coils at three frequencies for a series of load resistances. The curve indicates that for a Q in excess of 25, coil number one at 9 kc should not be loaded with less than 150,000 ohms. The parallel resonant impedance of the coil and tuning capacitance was reduced to the lowest practical limit by appropriate adjustment of L and C in order to minimize the reduction of Q with load. Similar curves can be drawn for coils of higher and lower frequencies. Since the load consists of three components for the modulator tuned circuit and two components for the harmonic generator tuned circuit, each component must have a higher impedance than the minimum permissible shunt impedance. Triodes are immediately ruled out for use as either modulator or harmonic generator because of low plate resistance. Pentodes, on the other hand, have plate resistances which in general are greater than 0.5 megohms and are thus suitable for use. The modulator tuned circuit has two other loads: one, the zero biased harmonic generator of low impedance; and two, the output amplifier which is so biased and driven as to provide an undistorted output.

The low impedance harmonic generator load can be isolated from the modulator very simply by means of an appropriate RC coupling network. The coupling capacitive reactance in ohms is made high (C small) to provide the high impedance isolation, and the grid return resistance of the harmonic generator is made sufficiently large to reduce voltage loss at the harmonic generator grid to less than three to one. This high impedance coupling network not only minimizes the modulator tank-circuit loading, but also simulates a generator of high impedance as far as the harmonic generator is concerned. Also the high driving impedance allows sharper clipping of the positive half of the sine wave enriching the harmonic content of the harmonic generator output. The type of coupling network described shifts the

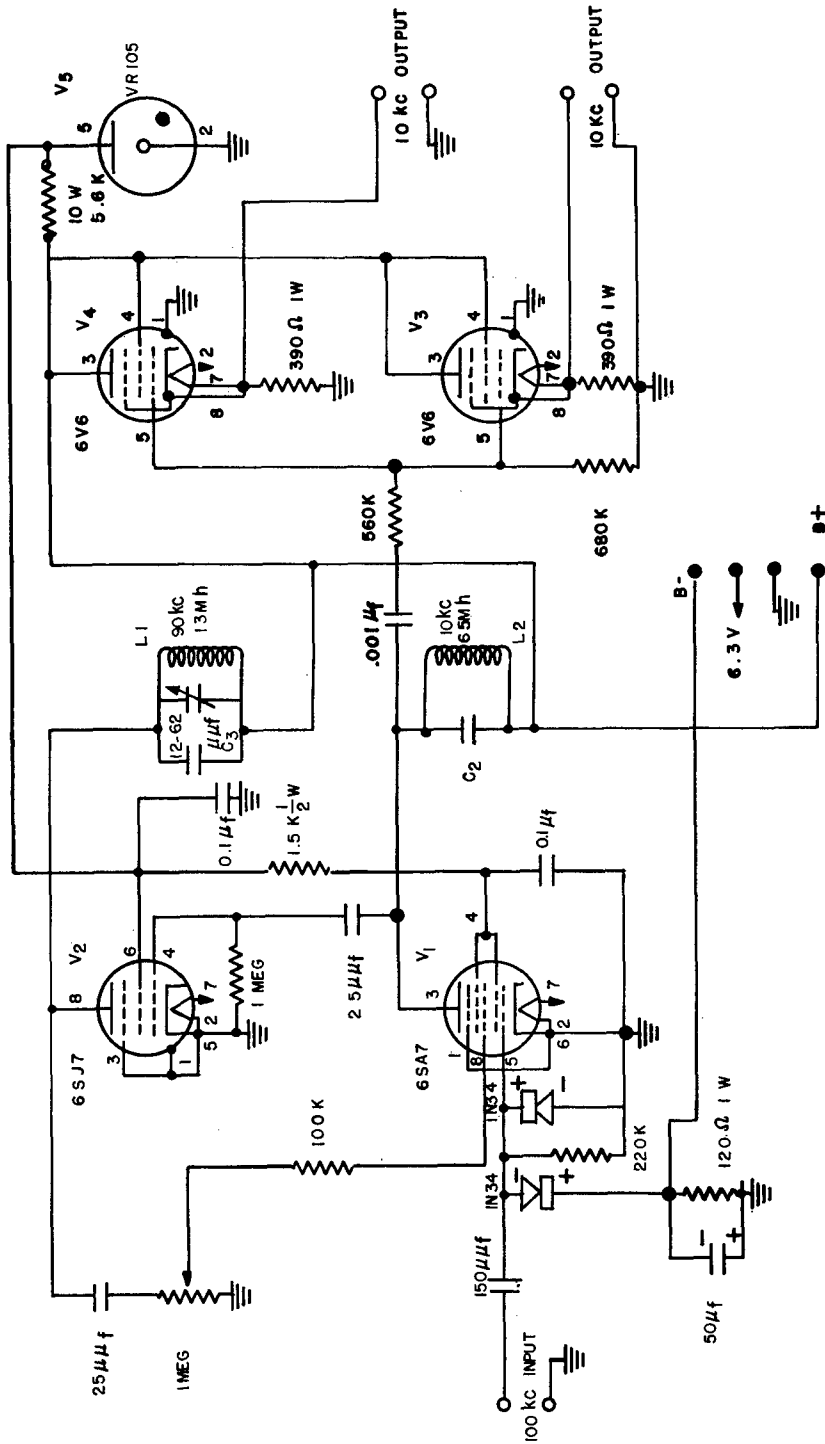


Figure 3 - Final 100- to 10-kc regenerative frequency divider

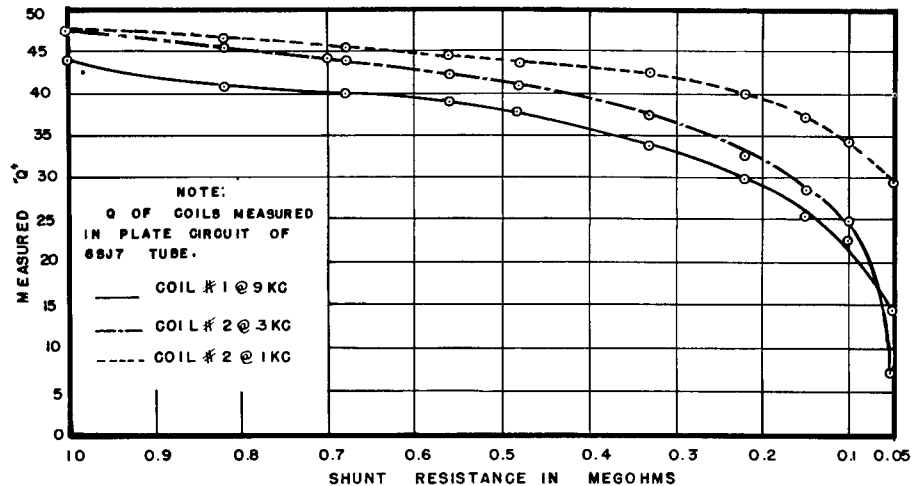


Figure 4 - Coil Q vs shunt load resistance

phase of the signal, without consequence. The isolation could have been realized with a series resistance in addition to a larger coupling capacitor which would have reduced the phase shift, but this feature was not found to be necessary. Loop phase relationships can more readily be controlled through tuning of the resonant circuits.

The output amplifier load, tubes V_3 and V_4 , on the modulator consists solely of the amplifier grid-return resistor since this amplifier is never driven to zero bias. Therefore, since the modulator output voltage is larger than that required to drive the amplifier, a stepdown in voltage is necessary. A simple RC coupling network will provide both stepdown in voltage and modulator tuned circuit isolation. The sum of reactance C in ohms and resistance R in ohms should be sufficiently high, as mentioned previously, and the ratio of C and R in ohms should be so selected as to provide the desired fraction of voltage at the amplifier grid. Here again the resulting phase shift is of no consequence. These simplified multipurpose coupling networks save components as well as simplify circuit design.

Means of minimizing the load on the harmonic generator output tuned circuit will next be considered. In addition to the pentode plate-resistance, this tuned circuit will be loaded by the modulator grid; however, this load can be isolated by high-impedance RC coupling. This coupling network differs from the two networks previously described in that a potentiometer is substituted for R, permitting any fraction of the harmonic generator output to be impressed on the modulator grid, and thereby furnishing a means of adjusting the loop gain. Phase shift does occur in the coupling network without deleterious effect.

The feedback signal of ample reverse amplitude is coupled to the modulator third grid rather than to the first grid which has higher transconductance. This arrangement, with the input signal impressed on the modulator first grid, results in extending the input voltage range to a lower value.

If a divider is constructed in accordance with the above design principles it will be found to perform well and it will be reproducible. However, observation will show that once the divider is operating it will work over a greater plate voltage and input-voltage range

than that range over which it is self-starting. An examination of the circuit will disclose that when the divider ceases to operate, an increase in plate and screen current occurs owing to the loss of signal bias in both the modulator and the harmonic generator. This shift, of course, will cause the screen voltage to drop, lowering the transconductance and therefore the loop gain, and thus make it more difficult to restart divider operation. An increase in input signal amplitude then will be necessary to restart the divider operation. This difficulty occurs mainly with plate voltages greater than 125 volts. It was remedied by regulating the screen voltage at a value of 105 volts, which also reduced the zero-biased tube currents to safe values under all conditions of operation.

A divider with screen regulation will operate over a large plate-voltage range but will still exhibit some self-starting instability with large input-voltage amplitudes. The reason for this instability is apparent when the change in modulator first-grid bias with input signal amplitude is considered. Negative bias will increase with signal amplitude which will reduce loop gain and tend to cause the divider to drop out of operation. It would be desirable to maintain this bias constant. This was accomplished by positive and negative input sine wave clipping with the clipper gate width (in volts) adjusted to a value just above the minimum unclipped operating level. Modulator bias was held satisfactorily constant with the double clipper.

The input signal double clipper has even a more important function in improving divider self-starting. Under starting conditions the sharply squared wave produced by the clipper shock excites the f/n selective circuit causing it to ring; and this, in turn, causes the harmonic generator to function normally, thus commencing divider operation. Therefore, the most important starting mechanism is actually the squared-wave shock exciting the f/n tuned circuit and initiating a ringing which is rapidly built to a stable level of operation. The squaring of the input sine wave was obtained by two germanium crystals connected to the modulator first grid, back to back, with the plus-clipping crystal grounded and the negative-clipping crystal returned to a negative bias obtained from a by-passed resistance in the B-minus lead. A resistance was inserted in series with the input lead to permit more efficient and perfect squaring. Actually, the coupling capacity may be made small to provide the desired impedance. The modulator first grid will clip positive peaks but not as efficiently as a crystal because of its higher forward resistance. Therefore, a positive peak clipping crystal was used.

No self-bias resistance was used in the modulator cathode because of the regulated screen operated at 105 volts to limit zero-bias plate and screen currents to safe values and because it permitted the input clipping circuit to function more efficiently. A distinct advantage existed in obtaining the clipper bias from a B-minus resistance in that the clipper gate width varied directly with plate voltage. This means that the modulator's operating bias was adjusted for optimum value at all plate voltages since it was small for reduced plate voltages and large for high plate voltages.

One other improvement was made in self-starting characteristics by decoupling the modulator screen grid from the harmonic generator screen grid to eliminate undesired coupling.

RESULTS OF TESTS ON THE FINAL REGENERATIVE FREQUENCY DIVIDERS

Two final regenerative dividers of each frequency, high (100 to 10 kc), mid (10 to 1.0 kc), and low (1.0 to 0.1 kc), were constructed in accordance with all of the preceding design considerations. Two cathode-follower output amplifiers were also provided on each unit to permit driving, and at the same time isolate two separate low-impedance loads. If plate

supply current drain is of importance, other output amplifier circuits of lower current drain may be employed. The final high-, mid-, and low-frequency dividers, respectively, are shown in schematic diagram form on Figures 3, 5, and 6. Figures 7, 8, and 9 show three-quarter views of the final high-, mid-, and low-frequency dividers, respectively. These photographs indicate the relatively small physical size, 3 x 15-1/2 x 4-1/2 inches high, and compactness of the units. Figure 10 is a bottom view of the low-frequency divider showing the simplicity of the wiring.

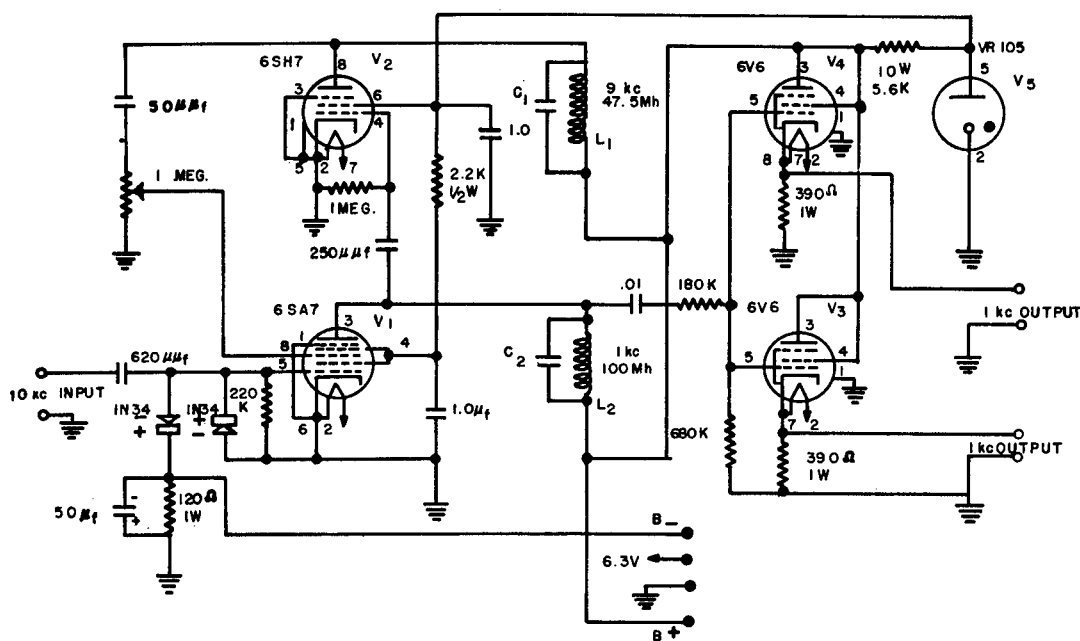


Figure 5 - Final 10- to 1.0-kc regenerative frequency divider

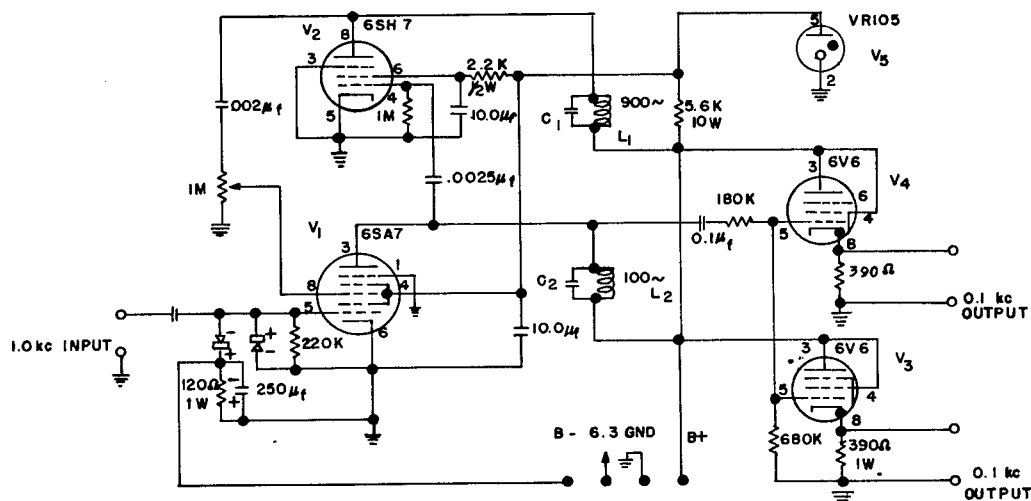


Figure 6 - Final 1.0- to 0.1-kc regenerative frequency divider

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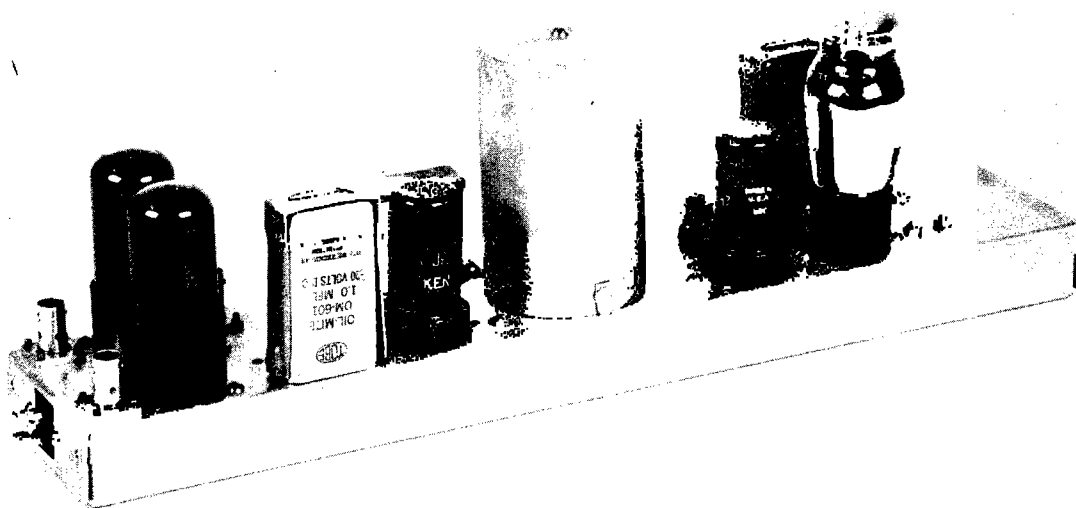


Figure 7 - Three-quarter view of the final 100- to 10-kc divider

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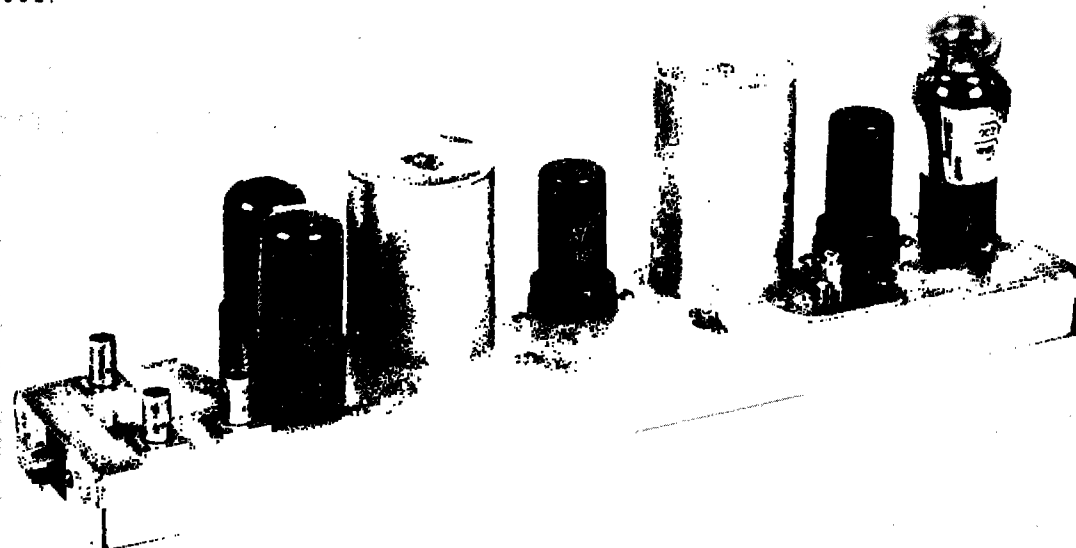


Figure 8 - Three-quarter view of the final 10- to 1.0-kc divider

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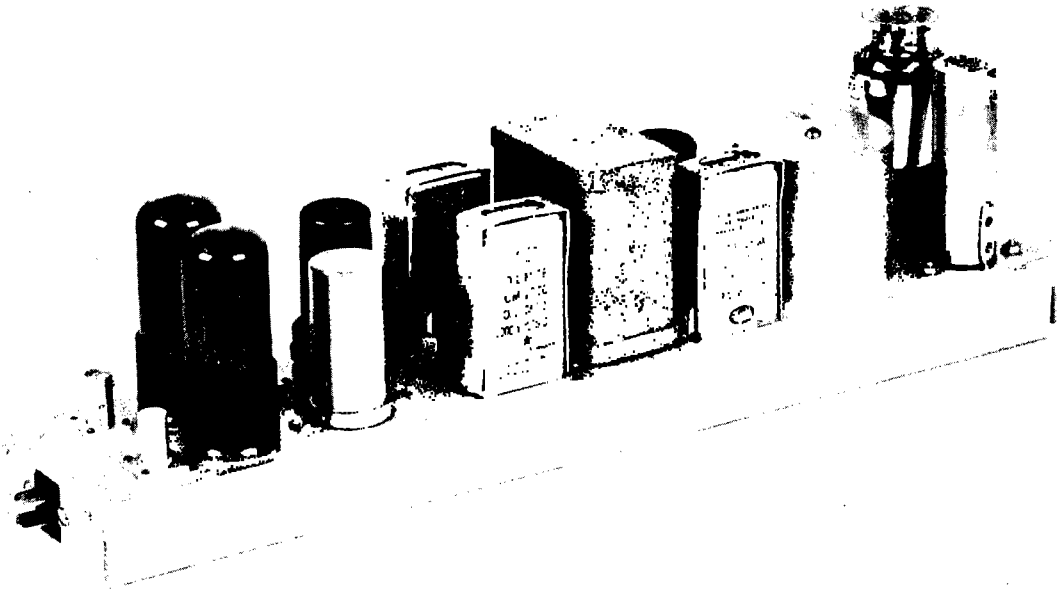
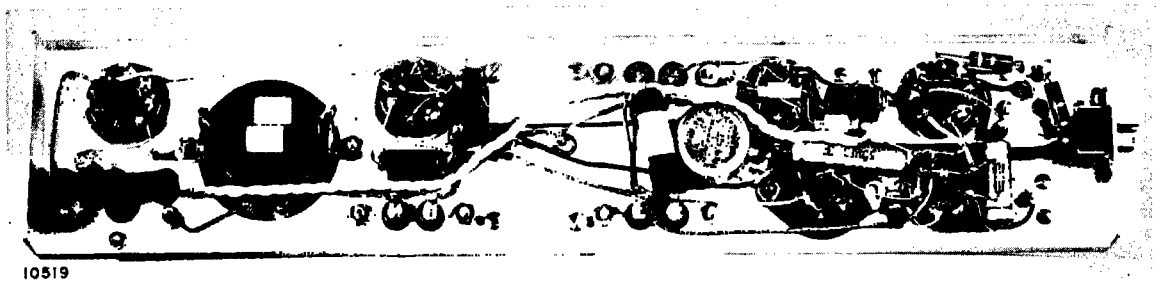


Figure 9 - Three-quarter view of the final 1.0- to 0.1-kc divider



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Figure 10 - Bottom view of the final 1.0- to 0.1-kc divider

Performance measurements also were made on all six dividers. Results obtained from the duplicate units were so nearly identical with the performance of the duplicated models that only one set of data will be presented for each pair of dividers. Measurements made to determine the output voltage for a series of input and plate voltages for which self-starting occurred are shown on Figures 11, 12, and 13 for the high-, mid-, and low-frequency dividers, respectively. On these figures, and on succeeding figures, data are not plotted for plate voltages above 350 volts because of power-supply limitations. Input voltage has not been plotted beyond 45 volts because of signal-generator limitations. The data show that the dividers commenced operating with as little as one or two volts of input and, under all conditions indicated, the output remained above 10 volts. Another interesting characteristic

is evident from the curves. It can be seen that, because of the double input clipping, the output voltage, with increasing input voltage, quickly rises to a maximum and thereafter remains constant.

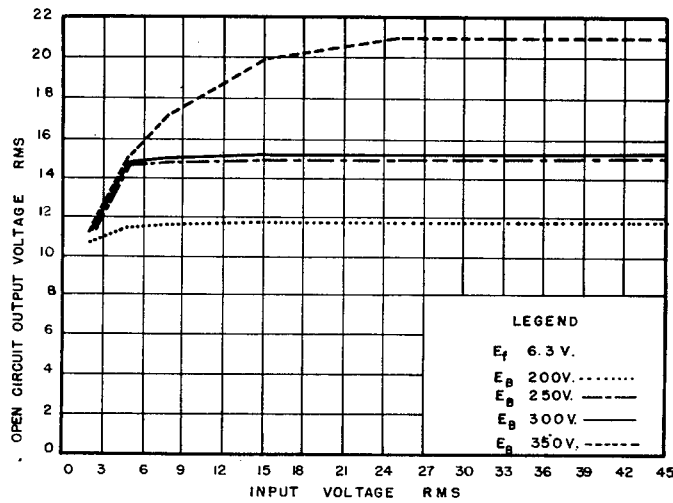


Figure 11 - Final high-frequency regenerative divider output voltage vs input voltage curves for four plate voltages

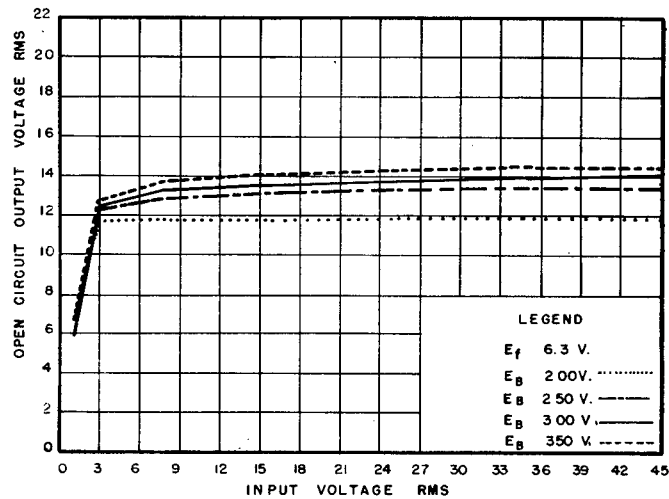


Figure 12 - Final mid-frequency regenerative divider output voltage vs input voltage curves for four plate voltages

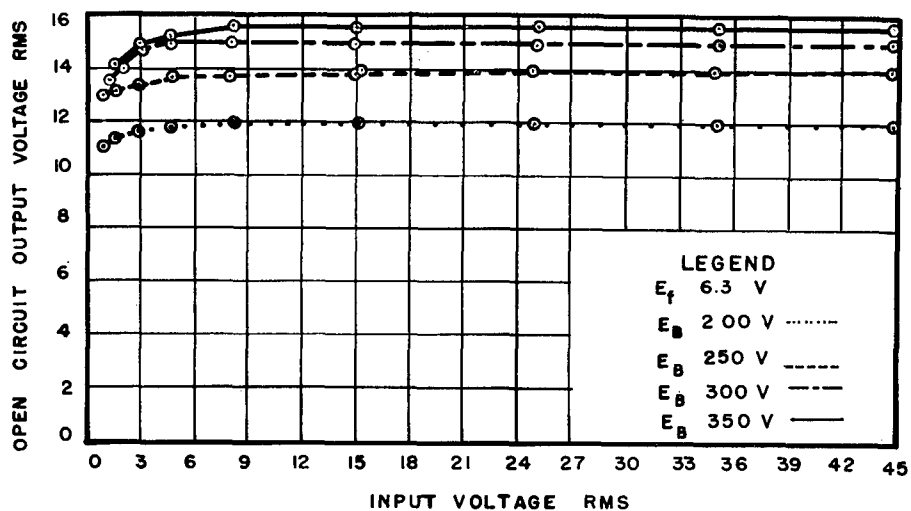


Figure 13 - Final low-frequency regenerative divider output voltage vs input voltage curves for four plate voltages

The divider self-starting range for all combinations of plate supply voltage and input voltage is shown in Figures 14, 15, and 16 for the high-, mid-, and low-frequency dividers respectively. These graphs show that the dividers will operate with plate voltages ranging from 40 volts to more than 350 volts and at the same time the input voltage can vary from one or two volts to more than 45 volts.

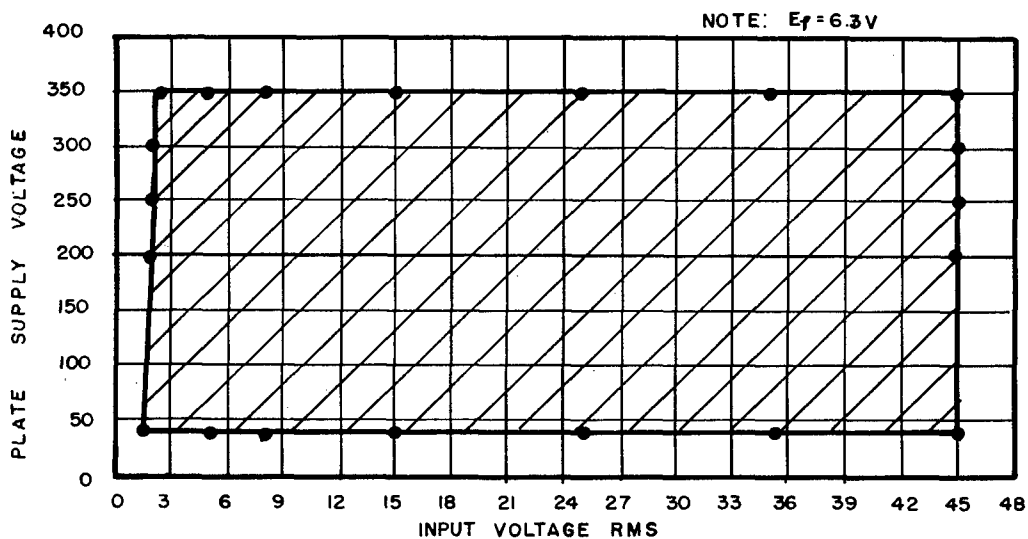


Figure 14 - Combinations of plate and input voltage for which the final high-frequency regenerative divider was self-starting

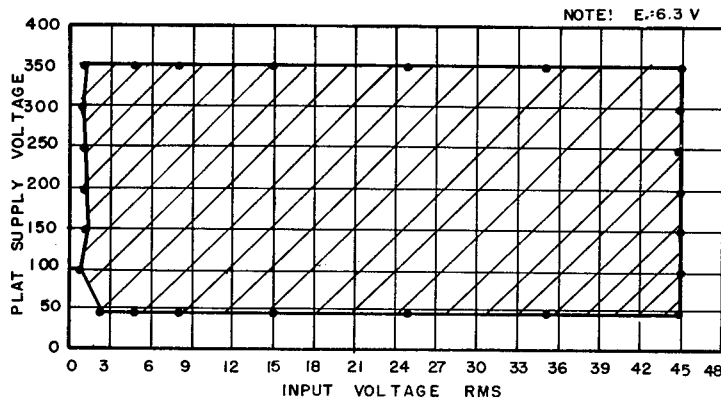


Figure 15 - Combinations of plate and input voltages for which the final mid-frequency regenerative divider was self-starting

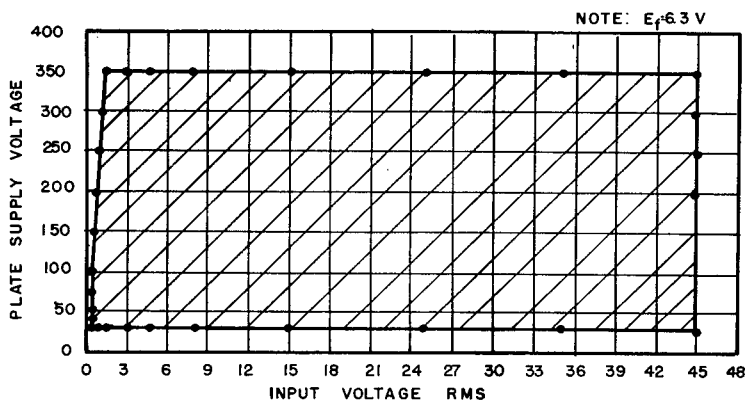


Figure 16 - Combinations of plate and input voltage for which the final low-frequency regenerative divider was self-starting

The data presented in the preceding six figures indicates not only uniformity of performance between pairs of dividers but also between the three dividers of different frequencies. The wide range of input and supply voltages over which the dividers are self-starting is of great advantage, for it not only allows a wide selection of operating voltages but permits the use of unregulated power supplies and also minimizes the harmful effects of tube and component aging. It should be emphasized that the dividers provided an output only in the area of operation plotted on the preceding graphs. At all other points the dividers were quiescent and provided no output.

Tables 1, 2, and 3 show the output voltage of the high-, mid-, and low-frequency dividers respectively, for open circuit, 2000 $\mu\mu\text{f}$, and 50-ohm loads shunted first across the measured output and secondly shunted across the unmeasured, second output. The procedures was next reversed and measurements were made on the second output. Data are also shown for a series of input voltages. As indicated, the capacitive load had no influence on output voltage. A 50-ohm load dropped the output voltage to about 25 percent of its original value, but this voltage was still ample to drive a succeeding divider directly without intermediate amplification. Normally a 50-ohm load is not shunted across a divider output. Some cross-coupling existed between outputs as indicated; however, it was found that this cross-coupling was due to the cathode followers' being driven to zero bias. When the input drive was slightly reduced, at the expense of a small drop in output voltage, all evidence of cross-coupling disappeared.

TABLE 1
Final High-Frequency Regenerative Divider
Output Voltage vs Load Characteristic

$E_B = 250 \text{ V.}$		$E_f = 6.3 \text{ V (RMS)}$			
Input to Divider in RMS Volts	No Load on Either Output	50-OHM Load on Output #1 No Load on Output #2	2,000- $\mu\mu\text{f}$ on Output #1 No Load on Output #2	No Load on Output #1 50-OHM Load on Output #2	No Load on Output #1 2,000- $\mu\mu\text{f}$ on Output #2
RMS Voltages at Output #1					
2.5	11.6	2.9	11.6	9.2	11.6
8.0	15.2	3.1	15.2	10.4	15.2
15.0	15.2	3.15	15.2	10.5	15.2
25.0	15.2	3.15	15.2	10.5	15.2
35.0	15.2	3.15	15.2	10.5	15.2
45.0	15.2	3.15	15.2	10.5	15.2
RMS Voltages at Output #2					
2.5	11.6	9.25	11.6	2.9	11.6
8.0	15.5	10.5	15.5	3.1	15.5
15.0	15.5	10.5	15.5	3.1	15.5
25.0	15.5	10.5	15.5	3.1	15.5
35.0	15.5	10.5	15.5	3.1	15.5
45.0	15.5	10.5	15.5	3.1	15.5

TABLE 2
Final Mid-Frequency Regenerative Divider
Output Voltage vs Load Characteristic

$E_B = 250 \text{ V.}$		$E_f = 6.3 \text{ V (RMS)}$			
Input to Divider in RMS Volts	No Load on Either Output	50-OHM Load on Output #1 No Load on Output #2	2,000- $\mu\mu\text{f}$ Load on Output #1 No Load on Output #2	No Load on Output #1 50-OHM Load on Output #2	No Load on Output #1 2,000- $\mu\mu\text{f}$ Load on Output #2
RMS Voltages at Output #1					
3.0	12.2	3.3	12.2	9.8	12.2
8.0	12.9	3.4	12.9	9.9	12.9
15.0	13.1	3.5	13.1	10.0	13.1
25.0	13.3	3.5	13.3	10.1	13.3
35.0	13.4	3.5	13.4	10.2	13.4
45.0	13.4	3.5	13.4	10.3	13.4
60.0	13.2	3.5	13.2	10.2	13.2
RMS Voltages at Output #2					
3.0	12.6	9.9	12.6	3.4	12.6
8.0	13.0	10.0	13.0	3.5	13.0
15.0	13.5	10.1	13.5	3.5	13.5
25.0	13.5	10.1	13.5	3.5	13.5
35.0	13.7	10.2	13.7	3.5	13.7
45.0	13.8	10.2	13.8	3.5	13.8
60.0	13.9	10.3	13.9	3.5	13.9

TABLE 3
Final Low-Frequency Regenerative Divider
Output Voltage vs Load Characteristic

$E_B = 250 \text{ V.}$ $E_f = 6.3 \text{ V (RMS)}$					
Input to Divider in RMS Volts	No Load on Either Output	50-OHM Load on Output # 1 No Load on Output # 2	2,000- μf Load on Output # 1 No Load on Output # 2	No Load on Output # 1 50-OHM Load on Output # 2	No Load on Output # 2 2,000- μf Load on Output # 2
RMS Voltages at Output # 1					
3.0	13.4	3.0	13.4	10.6	13.4
5.0	15.2	3.0	15.2	10.7	15.2
8.0	15.3	3.0+	15.3	10.8	15.3
15.0	15.3	3.0+	15.3	10.8	15.3
25.0	15.3	3.0+	15.3	10.8	15.3
35.0	15.3	3.0+	15.3	10.8	15.3
45.0	15.3	3.0+	15.3	10.8	15.3
60.0	15.3	3.0+	15.3	10.8	15.3
RMS Voltages at Output # 2					
3.0	13.9	10.1	13.9	2.65	13.9
5.0	14.0	10.3	14.0	2.7	14.0
8.0	14.1	10.4	14.1	2.7+	14.1
15.0	14.2	10.5	14.2	2.7+	14.2
25.0	14.2	10.6	14.2	2.7+	14.2
35.0	14.2	10.6	14.2	2.7+	14.2
45.0	14.2	10.6	14.2	2.7+	14.2
60.0	14.2	10.6	14.2	2.7+	14.2

Mention should be made of the ease in tuning of the final dividers. The alignment of the final divider was readily accomplished without an oscilloscope for wave form monitoring. A practical leeway existed in the tuning of the two tuned circuits which permitted them to be fixed tuned with divider operation assured for wide temperature variations as well as for factors already graphically portrayed. The setting of the feedback potentiometer was also noncritical. It should also be pointed out that these dividers possess excellent phase stability and in addition do not require filters to clean up the output wave form.

CONCLUSIONS

From measurements performed on six models of the subject regenerative frequency divider, it is concluded that ten-to-one regenerative frequency dividers below 100 kc can

be constructed to provide the following characteristics:

- (1) Stable operation for plate voltage variations of 40 to more than 350 volts.
- (2) Stable operation for signal input voltage variations of one or two to more than 45 volts.
- (3) Self-starting over any combination of the above voltage ranges.
- (4) No indication of self-oscillation in the absence of an intended input signal.
- (5) Sufficient output voltage, without additional amplification, to drive succeeding dividers under all conditions.
- (6) Noncritical alignment. Sufficient tuning tolerance exists to permit fixed tuned circuits. Loop gain adjustment is also noncritical.
- (7) Small physical size - 3 x 15-1/2 x 4-1/2 inches high.
- (8) Reproducible design.

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